Title of Investigation:

Active Atmospheric Methane Sounder Using a Fiber Laser-Pumped Optical Parametric Oscillator

Principal Investigator:

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Other External Collaborators:

None

Initiation Year:

FY 2005

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$60,000

Funding Authorized for FY 2005:

$60,000

Actual or Expected Expenditure of FY 2005 Funding:

In-house: $60,000

Status of Investigation at End of FY 2005:

To transition to other funding: ESTO ACT, Code S PIDDP, and/or Mars Scout

Purpose of Investigation:

The term "global warming" refers to the accelerated warming of Earth's atmosphere and is believed to be the result of an increase in certain atmospheric gases. Carbon dioxide (CO_2) and methane (CH_4) are two gases that strongly absorb Sun and Earth thermal (infrared) energy.

Because these gases absorb (hold) the heat, their impact on global warming is sometimes called the "greenhouse" effect. (Greenhouses get warm because visible sunlight gets in, but infrared (heat) radiation doesn't get through glass.) Not surprisingly, dramatic changes in CO_2 and CH_4 concentrations in the past are accompanied by similar changes in Earth's climate (Figure.1). Therefore, long-term measurements of CO_2 and CH_4 on a global scale are very important. Already, local data from numerous locations worldwide indicates that carbon dioxide and methane concentrations have nearly doubled over the past 150 years (Figure. 2).

To cover the entire globe easily and quickly, our ultimate goal is to make these measurements from orbit (Figure 3). We have been working on a method for remotely measuring CO_2 using lasers. This method is similar to those used in modern fiber-optic telecommunications. The purpose of this investigation is to develop a laser using similar fiber-optic technology so that we can measure methane remotely. Using fiber-optic technology allows the laser to be lightweight, efficient, low-cost, and reliable.

Methane also is of interest for planetary science since it is a major constituent in the atmospheres of the outer planets (Uranus, Neptune). In addition, it recently was discovered on Mars (Figure. 4), where it could help to locate evidence of past or present life. In addition, understanding the Martian atmosphere helps improve atmospheric models that can be applied to the Earth.

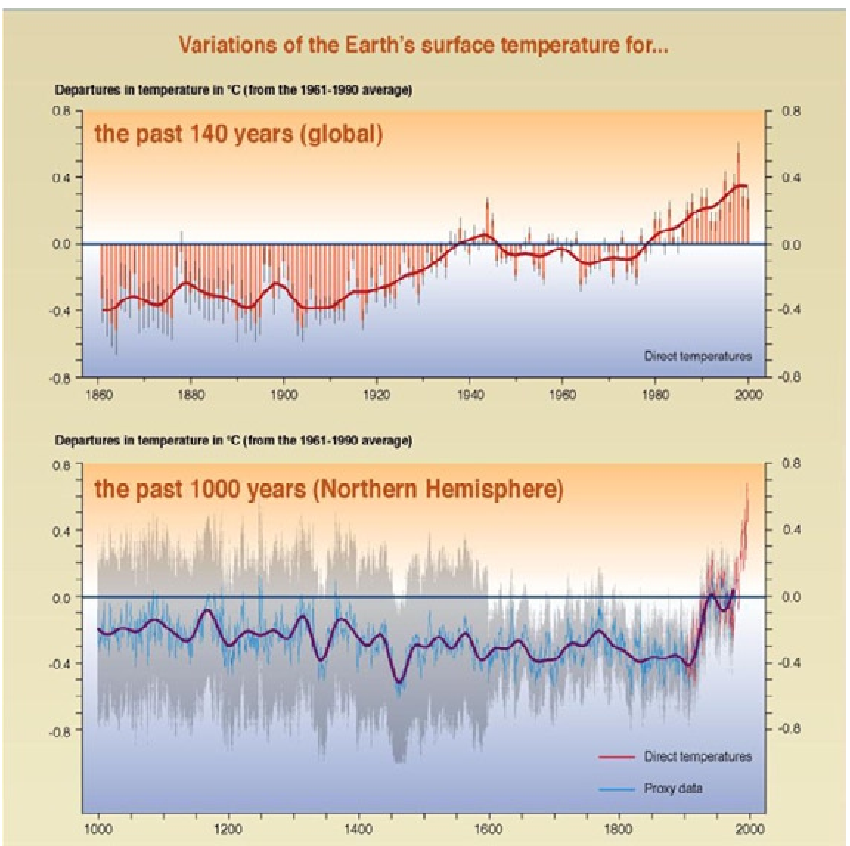

Figure 1. Variations in the Earth's temperature in the past

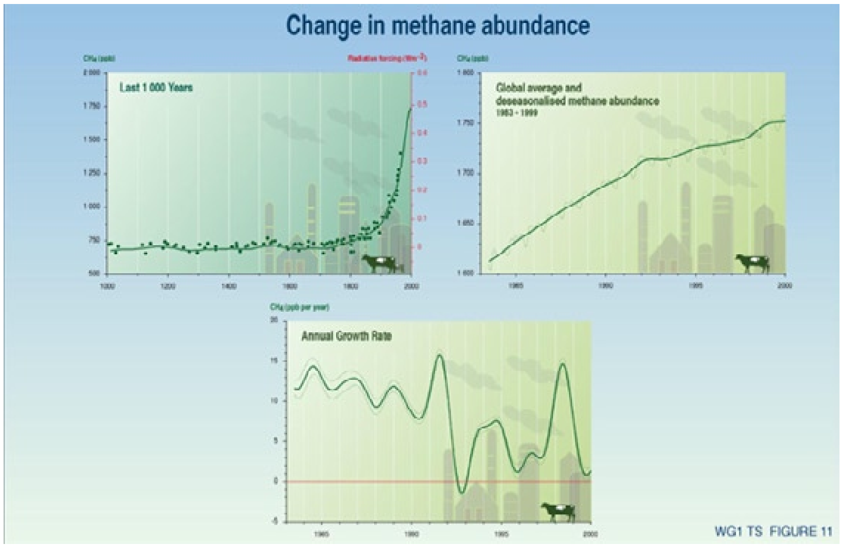

Figure 2. Changes in methane abundance in the past

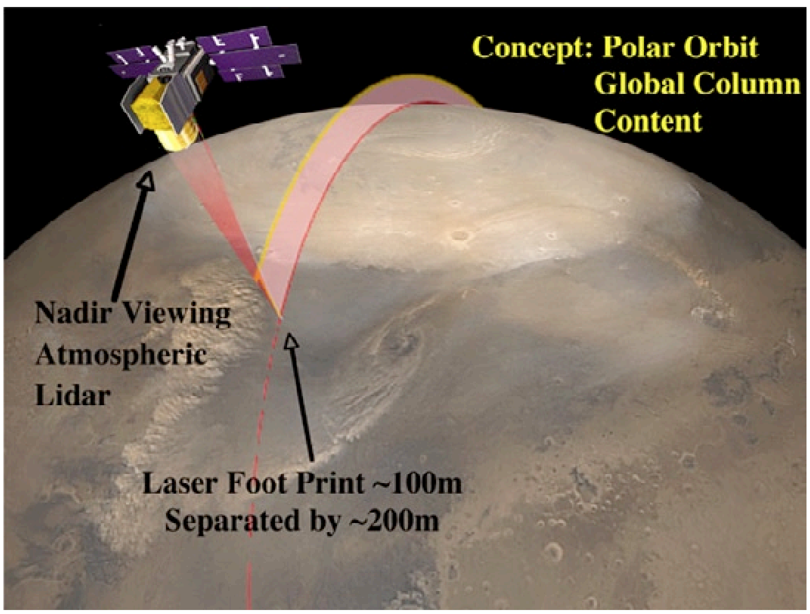

Figure 3. Laser sounder satellite instrument concept for measuring atmospheric gases (e.g., methane) from orbit (e.g., Earth or Mars)

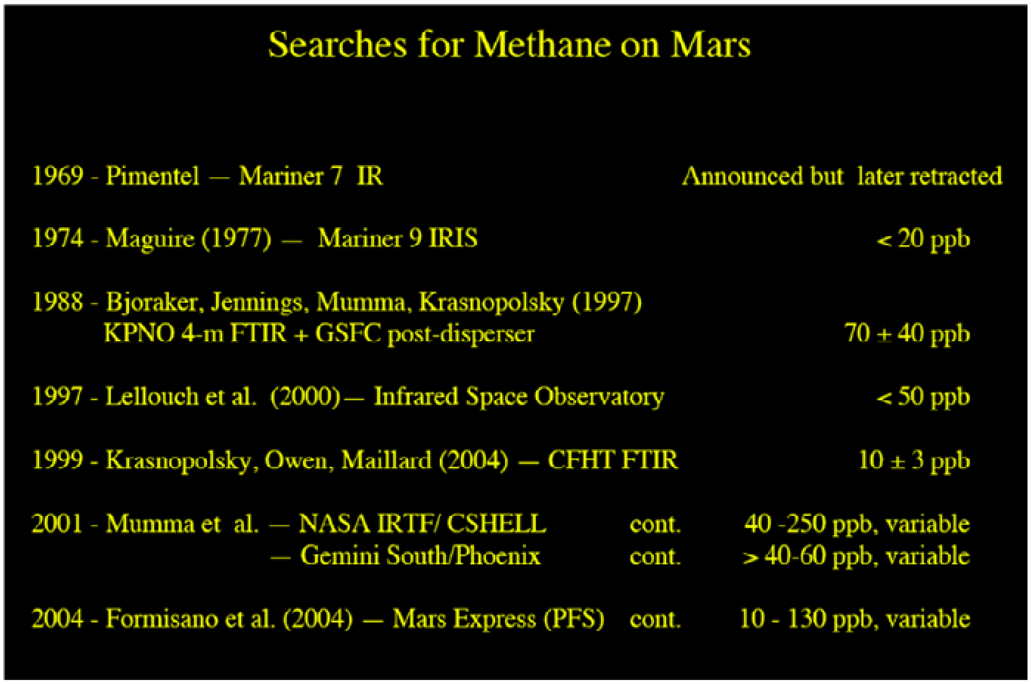

Figure 4. History of search for methane on Mars (Courtesy of Dr. Michael Mumma)

Accomplishments to Date:

First, we measured methane (from a gas cylinder) in a multi-pass optical cell with an external cavity tunable laser-diode using the differential absorption technique.

Our technique for measuring methane is to scan the wavelength of a laser-transmitter source over the range required. Simultaneously, we detect the light to observe the change in transmission of the light intensity caused by the absorption of the light by one of the overtones (Figure 5) of the molecular vibration/rotation frequencies. This technique is known as differential absorption.

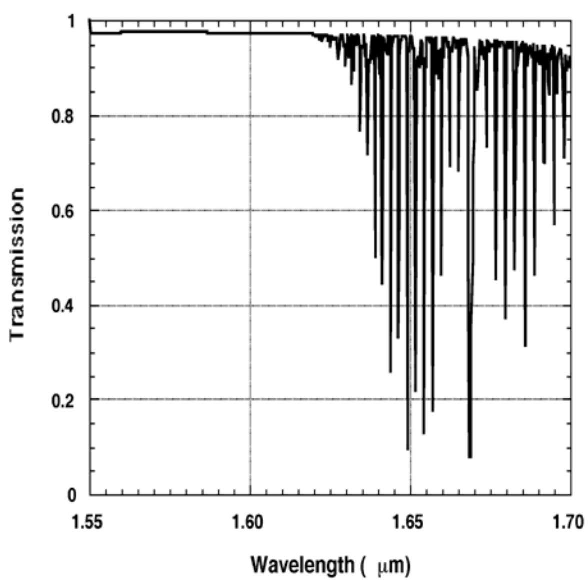

Figure 5. Methane R4 manifold (absorption lines) near 1.65 micron wavelength

Our initial methane measurement experiment was to make this differential absorption measurement on 3 percent (non-flammable) methane gas mixed with nitrogen in a multi-pass optical cell (Figure 6).

Second, we measured Earth's atmospheric methane over a 200-m open path using a low-power 1650-nm distributed feedback (DFB) laser-diode transmitter.

After measuring 3 percent methane gas (at reduced pressure) by scanning various absorption lines over a 10-m multi-pass path in an optical cell, we then measured nominal methane levels (1.7 parts per billion = 0.000000017 percent) in the real atmosphere over a 412-m path (Figure 7) using differential absorption on the strongest (1650 nm) line. Third, we designed and built a widely tunable narrow-linewidth laser source that is scalable to high power (>1 W) and capable of at operating at both 1650 nm and 3250 nm (Reference 1).

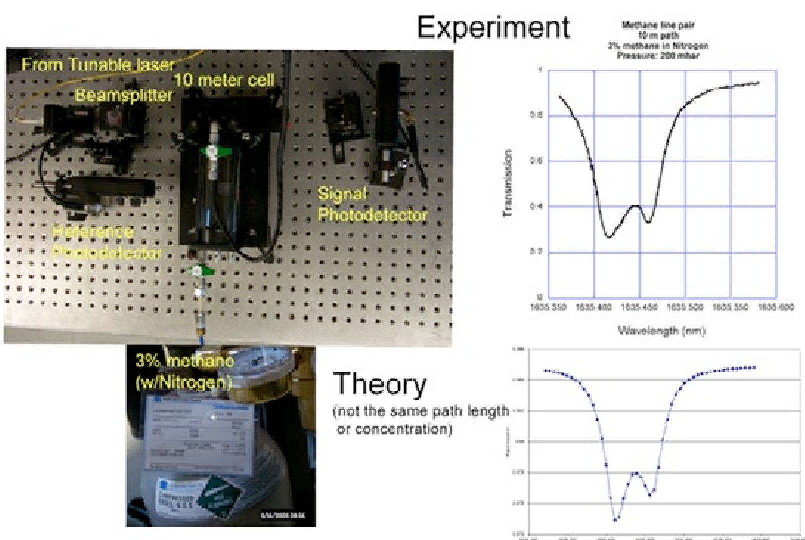

Figure 6. Experimental set-up for using a tunable diode laser to measure 3 percent methane gas (mixed with nitrogen) absorption feature near 1635 nm in 10-m multi-pass cell and comparison

Our goal is to enable methane measurements from planetary orbits using our laser sounder instrument. To achieve this, we need a high-power, tunable, narrow linewidth laser transmitter that operates over the required wavelength regions for measuring methane absorption lines. Our chosen laser-transmitter approach is a master-oscillator power-amplifier (MOPA) pumped optical-parametric-oscillator (OPO). The master oscillator is an external cavity tunable semiconductor-diode laser. The power amplifier is a diode-pumped ytterbium (Yb) fiber optic amplifier (Figure 8). The OPO is a simple two-mirror cavity laser, with a high-temperature-controlled oven containing a periodically poled lithium-niobate crystal (Figure 9) for the nonlinear optical wavelength conversion.

The wavelength of the OPO light output is a function of several parameters, including the pump wavelength (tunable by the master oscillator) and the grating period of the PPLN, which can be finetuned with the oven temperature and the mirror reflectivity and absorption (Figures 10 and

11). With the proper nonabsorbing mirrors (not yet purchased), light output can be achieved at both near-infrared (near 1650 nm) and mid-infrared (3250 nm) wavelengths. Using the low-cost readily available mirrors we purchased, we could only achieve light output near 1650 nm. Since methane concentrations are very low on both Earth and Mars, the use of 3.25-micron wavelength light would allow improved detection sensitivity because the methane-absorption line strength is 100 times larger at 3.25 microns compared with 1.65 microns (Figure 12).

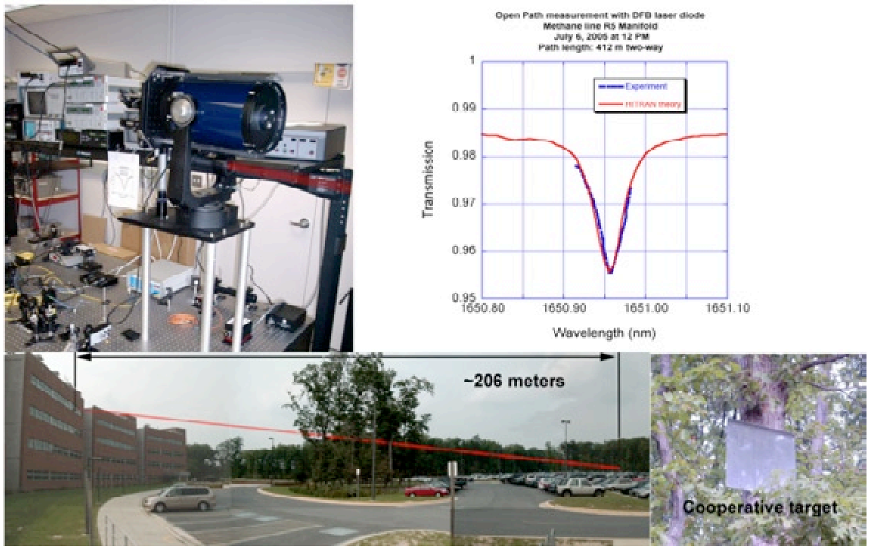

Figure 7. Laser sounder prototype instrument for measuring atmospheric methane. Upper left: Laser and transmit and receive telescopes. Upper right: Real-time experimental open-path measurement of atmospheric methane spectra over a 206-m one-way path compared to theory. Lower left: 206-m open-path test range from fourth-floor window to cooperative target. (Laser path is drawn in red.) (Note: Laser light is invisible and at eye-safe wavelength) Lower right: Microprism-retroreflector tape cooperative target at far end of test range.

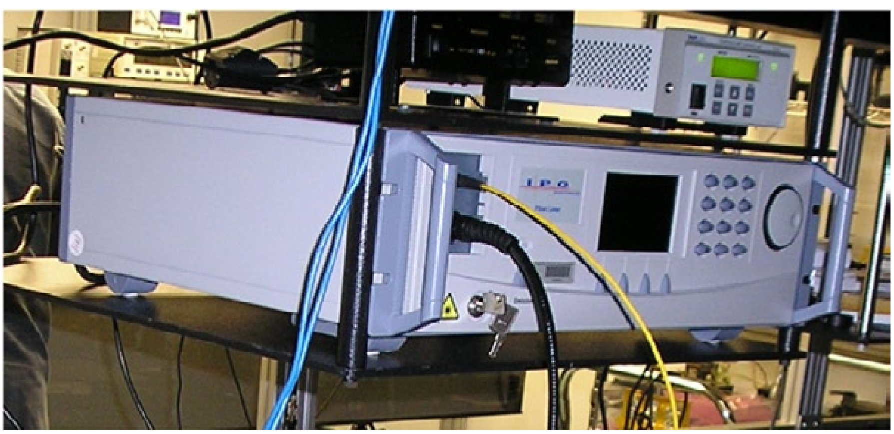

Figure 8. 10 W polarization-maintaining ytterbium (Yb) fiber-optic amplifier for pumping optical-parametric-oscillator (OPO)

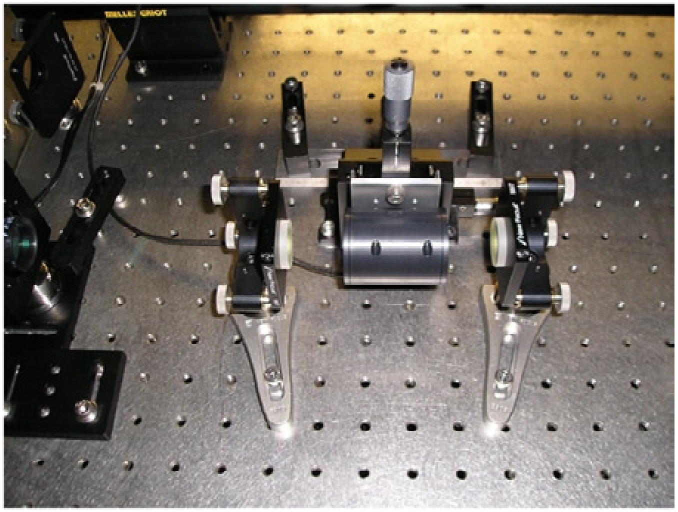

Figure 9. Optical-parametric-oscillator (OPO) consisting of a two-mirror cavity and a temperature-controlled periodically poled lithium-niobate crystal for nonlinear optical-wavelength conversion

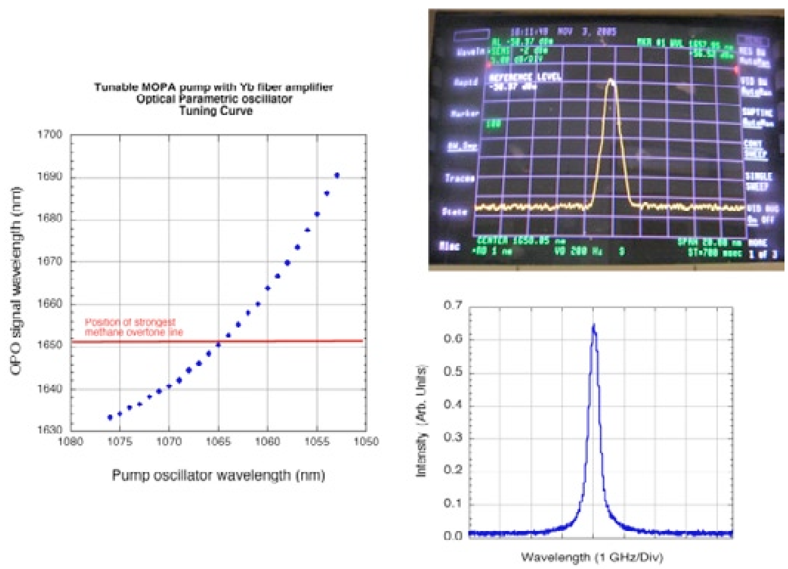

Figure 10. Experimental optical-parametric-oscillator spectral data Left: Tuning curve showing that wavelength range more than covers numerous R4 manifold methane lines (see Figure 5) Upper right: Measured OPO light output spectra using optical spectrum analyzer (1.0 nm resolution) Lower right: Measured OPO light output spectra using Fabry-Perot optical spectrum analyzer (50 MHz resolution) demonstrating single-frequency output

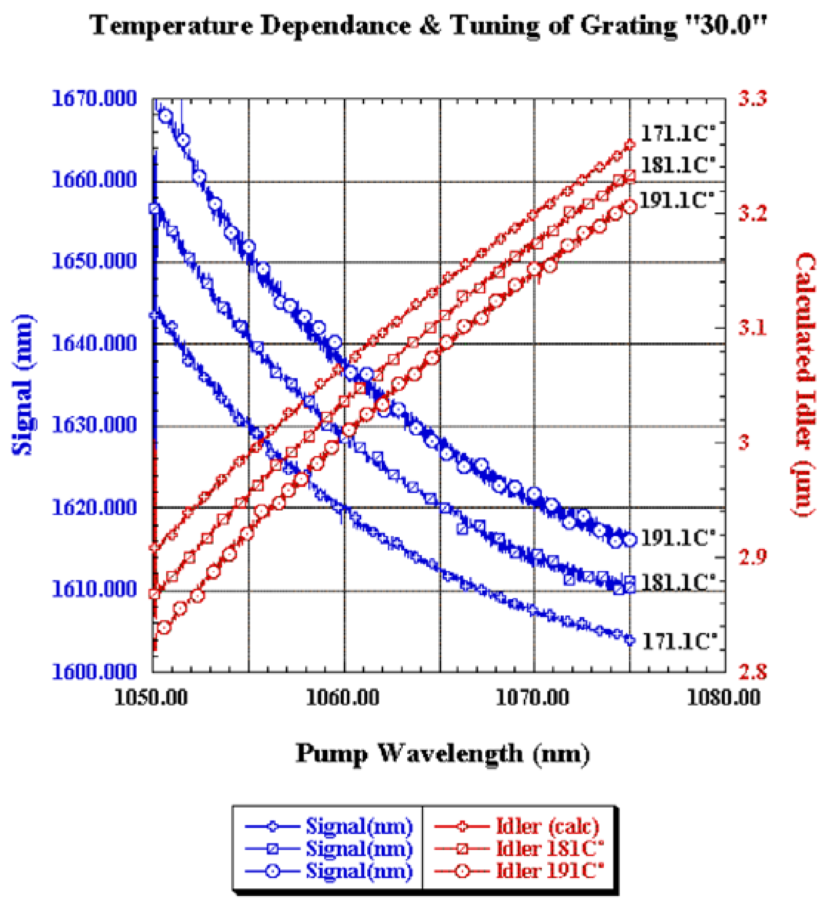

Figure 11. Measured OPO signal output wavelength (left-side ordinate) as a function of master oscillator wavelength for the 30.0-micron periodically poled lithium-niobate crystal grating spacing at three different crystal temperatures. Right-side ordinate shows calculated idler OPO output wavelength as a function of master oscillator wavelength. This can be achieved by using mirrors with the proper transmission and coatings in the mid-infrared (i.e., near 3 microns).

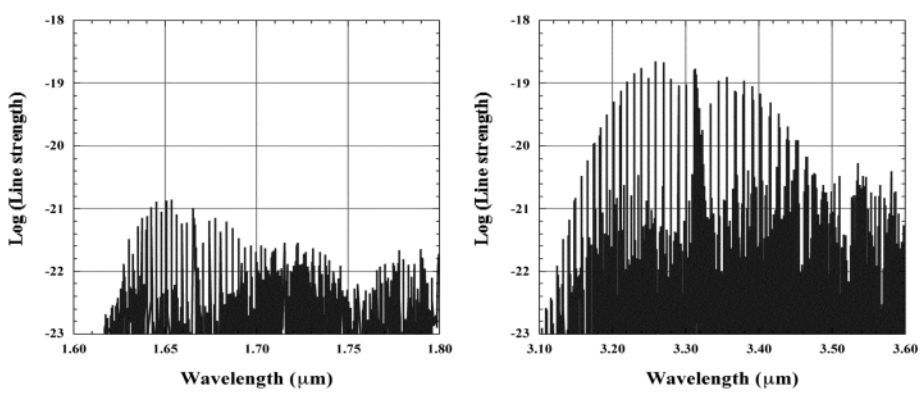

Figure 12. These charts compare methane-absorption line strengths near 1.65 and 3.25 micron wavelengths. The absorption line strength is more than 100 times stronger at the 3.25-micron wavelength. The 3.25-micron wavelength region is accessible with the OPO idler light output.

References:

1. Lindsay ID, et al., "110GHz rapid, continuous tuning from an optical parametric oscillator pumped by a fiber-amplified DBR diode laser," *Optics Express* **13** (4): 1234-1239 (2005).

Publications that included work from this DDF:

Michael A. Krainak, James Abshire, Graham R. Allan, Mark Stephen, "Fiber lasers and amplifiers for science and exploration at NASA Goddard Space Flight Center," *18th Solid State and Diode Laser Technology Review Technical Digest,* Directed Energy Professional Society paper Fiber-5, June 2005.

Michael A. Krainak, James Abshire, Graham Allan, John Burris, G. James Collatz, Amelia Gates, Randy Kawa, Haris Riris, Xiaoli Sun, "Remote Sensing Of Atmospheric Carbon Dioxide And Methane Using Tunable Diode Lasers, Fiber Amplifiers And Photon Counting Detectors," Tunable Diode Laser Spectroscopy Conference, July 2005.

Planned Future Work:

In the near future, we will optimize OPO optical power output near the 1.65-micron wavelength by purchasing mirrors with a different reflectivity. We will reduce thermal gradient-related issues by purchasing a magnesium-doped periodically poled lithium-niobate crystal to enable room temperature operation of the OPO crystal. To optimize OPO optical output power near the 3.25-micron wavelength, we will purchase mirrors that do not absorb in the mid-infrared. We will make real-time methane measurements (both in cell and open-path) at the 1.65-micron wavelength using the OPO light output. To further enable methane measurements at the 3.25 micron wavelength, we will obtain a mercury cadmium telluride (HgCdTe) detector. Finally, we will make real-time methane measurements (both in cell and open-path) at the 3.25-micron wavelength using OPO output and HgCdTe detector.

Key Points Summary:

Project's innovative features: The first innovation is the use of the new instrument idea we call a "laser sounder." The laser sounder instrument provides much more light at the optical receiver (compared with today's large-pulse laser instruments) because it uses the strong "echo" (thus the "sound-er" name) reflection from the planetary surface (rather than the very weak reflections from the "clear" atmosphere) to measure atmospheric gases. It also permits us to measure gas concentration as a function of height. This takes advantage of the fact that absorption lines are broader at lower altitudes compared with high altitudes due to differences in atmospheric (on Earth: air) pressure. Highly precise measurements of atmospheric gas concentrations are enabled because the laser-spectral width is much narrower than the gas-absorption line. In addition, day and night measurements are possible since the laser (rather than the Sun) is used as the instrument light source. These two latter points are distinct advantages over the common (passive spectrometer) instruments in use today.

The second innovation is the use of the tunable-fiber transmitter pump to capitalize on the numerous advantages of fiber lasers (light-weight, efficient, low-cost, reliable) and to leverage the multi-billion dollar commercial and defense industry investments. The laser-sounder concept permits use of a low peak-power laser source that also is a favorable operating mode for fiber lasers. It also permits the use of ultra-sensitive time-integrating detectors that are highly developed (space-qualified) for use at both near and mid-infrared wavelengths.

The third innovation is the use of both the signal and idler wavelengths of the new (optical-parametric-oscillator) laser light output permitting short-term measurements at the near-infrared wavelength (color) and extension to the mid-infrared wavelengths ("more red" color) where the absorption lines are 100 times stronger (making methane detection and measurement much easier).

Potential payoff to Goddard/NASA: High-precision, global methane measurements are highly desirable for planetary science. For Earth, this enables scientists to track methane levels to monitor the impact on global warming. For Mars, it enables scientists to possibly locate evidence of past or present life. We are currently investigating using this instrument for the 2011 Mars Scout opportunity. The new (ytterbium) fiber lasers, which we used as one part of our laser system, have recently been space-qualified in both the U.S. and Europe. In addition, this laser source has wide application in human-health monitoring for non-invasive blood (similar to the Star Trek tricorder), breath and urine analysis. It also can be used for medical-diagnostic imaging.

The criteria for success: This project has been very successful. We demonstrated measurements of methane that agreed with predictions on both the optical bench in our lab and over a long path (remotely) through the open air (atmosphere) using a new laser (sounder) instrument. For the open-air measurements we used a highly reflecting target since we didn't have enough light intensity (power) at this time to use reflections from natural objects (trees, rocks, water, ice). We separately designed and built a new type of high-power laser (ytterbium fiber laser pumped optical-parametric-oscillator) to enable methane measurements using natural object reflections. This new laser is capable of operating at the correct wavelengths (colors) and power (intensity) to make remote measurements of methane (ultimately from orbit). We ran out of time before we could demonstrate the same methane measurements using our new (higher-power and multiple color (wavelength)) laser, but we plan to do this in the near future. Our ultimate success would be to enable global methane measurements from a laser-sounder instrument in planetary (e.g. Earth or Mars) orbit.

Technical risk factors: Although we knew we would have enough laser optical power to make methane measurements on our optical bench, it was not obvious that we would have enough optical power to make methane measurements over our open-air test range using a commercial low-power laser. It also was not clear that we could purchase a low-power laser that operated at the correct wavelength (the strongest line near 1650 nm) to measure methane remotely. To reduce this risk, we purchased low-power lasers from several companies.

Designing and building the optical-parametric-oscillator (OPO) had several risks. Since none of us had ever designed and built an OPO, it was not clear that we had the proper understanding of the important factors to make our first system operate. To save money and time, we purchased a standard periodically poled lithium-niobate crystal. This lower-cost, more widely available crystal has to be operated at high temperatures to avoid a known non-permanent damage mechanism (the photorefractive effect). The high-operating temperature causes thermal gradients in the air that lead to laser-light output (wavelength and power) instability. Therefore, it was not clear that we could achieve the single-frequency operation required for high-quality methane measurements. The OPO laser-cavity design optimization was not fully understood since we had difficulty estimating the transmission losses associated with the OPO crystal. To reduce this risk, we purchased mirrors with several different reflectivities. Although we purchased enough mirrors to successfully build and operate the OPO, we are not at the optimum reflectivity for achieving the highest possible output power. We understood this better after measuring the losses from the OPO crystal.